

# QCD dynamics at low $x_{Bj}$ in $ep$ collisions at HERA

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Forward jet and multijet production has been measured at low Bjorken  $x$  at HERA. The measured cross sections and correlations were compared to predictions from DGLAP-based fixed-order calculations. Further comparisons were made to DGLAP-based and CCFM-based leading-order Monte Carlo predictions, as well as to Colour-Dipole model predictions. For the majority of the phase space covered in the HERA kinematic region, fixed-order calculations describe the data well, while the leading-order models provide an inconsistent description of the data.

## 1 Introduction

Jet production in DIS is an ideal environment for investigating different approaches to parton dynamics at low Bjorken- $x$ ,  $x_{Bj}$ . An understanding of this regime is of particular relevance in view of the startup of the LHC, where many of the Standard Model processes such as the production of electroweak gauge bosons or the Higgs particle involve the collision of partons with a low fraction of the proton momentum.

In the usual collinear QCD factorisation approach, the cross sections are obtained as the convolution of perturbative matrix elements and parton densities evolved according to the DGLAP evolution equations. In these equations, all orders proportional to  $\alpha_s \ln Q^2$  and terms with double logarithms  $\ln Q^2 \cdot \ln 1/x$ , where  $x$  is the fraction of the proton momentum carried by a parton, which is equal to  $x_{Bj}$  in the quark-parton model, are resummed. In the DGLAP approach, the parton participating in the hard scattering is the result of a partonic cascade ordered in transverse momentum,  $p_T$ . The partonic cascade starts from a low- $p_T$  and high- $x$  parton from the incoming proton and ends up, after consecutive branching, in the high- $p_T$  and low- $x$  parton entering in the hard scattering. At low  $x_{Bj}$ , where the phase space for parton emissions increases, terms proportional to  $\alpha_s \ln 1/x$  may become large and spoil the accuracy of the DGLAP approach. In this phase-space region, a better description may come from the BFKL approach, which resums terms proportional to  $\ln 1/x$ , and the CCFM approach, which uses unintegrated gluon densities in an all-loop non-Sudakov resummation.

Parton evolution schemes at low  $x_{Bj}$  were studied at HERA by measuring forward jet production and correlations in jet angles and transverse momentum. An excess of forward jets compared to DGLAP-based predictions and jets produced in the hard scatter that are not strongly correlated in transverse momentum may indicate the breakdown of DGLAP dynamics.

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## 2 Dijet Azimuthal Correlations

Dijet azimuthal correlations were investigated by the H1 Collaboration<sup>1</sup> by measuring the cross-sections  $d^2\sigma/dx_{Bj}d\Delta\phi^*$ , where  $\Delta\phi^*$  is the azimuthal separation in the hadronic centre-of-mass (HCM) frame between the two selected jets closest to the scattered electron in pseudorapidity,  $\eta$ . The measurements of  $\Delta\phi^*$  are reasonably well-described by NLOJET<sup>2</sup> calculations at  $\mathcal{O}(\alpha_s^3)$ , albeit within large theoretical uncertainties. To reduce the theoretical uncertainties, the measurements were normalised to the visible cross section for  $\Delta\phi^* < 170^\circ$ . With a reduced theoretical uncertainty, the calculations are shown to predict a narrower  $\Delta\phi^*$  spectrum than is measured, especially at very low  $x_{Bj}$ , as shown in Fig. 1. The measurements were also compared to predictions from two RAPGAP<sup>3</sup> (DGLAP) samples, with one sample using only direct photons, the other using both direct and resolved photons; LEPTO<sup>4</sup> (CDM); and CASCADE<sup>5</sup> (CCFM). All models fail to describe  $\Delta\phi^*$  over the entire range in  $x_{Bj}$  covered.

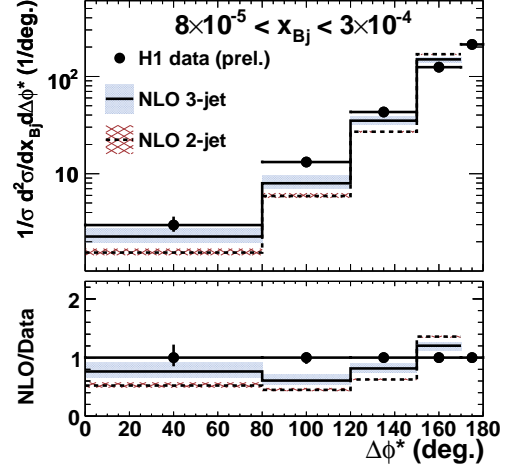


Figure 1: Double-differential normalised (see text) cross sections as a function of  $\Delta\phi^*$  as measured by H1 compared to NLOJET calculations for  $\mathcal{O}(\alpha_s^2)$  and  $\mathcal{O}(\alpha_s^3)$ .

## 3 Multijet Correlations

The sensitivity of parton evolution to the topology of the jet system was studied by the ZEUS collaboration<sup>6</sup>. Multi-differential cross sections as functions of the jet correlations in transverse momenta, azimuthal angles, and pseudorapidity have been measured for dijet and trijet production in the HCM frame. DGLAP-based calculations from NLOJET at  $\mathcal{O}(\alpha_s^2)$  and  $\mathcal{O}(\alpha_s^3)$  were compared to the measurements. The NLOJET calculations at  $\mathcal{O}(\alpha_s^2)$  do not describe the correlations in transverse momenta and azimuthal angle for dijet events; however with inclusion of higher-order terms, the NLOJET calculations at  $\mathcal{O}(\alpha_s^3)$  describe the dijet data over the entire range in  $x_{Bj}$  covered. The importance of higher-order terms at low  $x_{Bj}$  is seen especially when measuring the double-differential cross sections in  $Q^2$  and  $x_{Bj}$  for events with  $\Delta\phi_{HCM}^{\text{jet1,2}} < 120^\circ$ , where  $\Delta\phi_{HCM}^{\text{jet1,2}}$  is the azimuthal separation of the two jets with the highest transverse energy. At low  $x_{Bj}$ , the NLOJET calculations at  $\mathcal{O}(\alpha_s^3)$  are up to about one order of magnitude larger than the  $\mathcal{O}(\alpha_s^2)$  calculations and are consistent with the data, as seen presented in Fig. 2. The NLOJET calculations at  $\mathcal{O}(\alpha_s^3)$  also provide a reasonable description of the trijet measurements, with the description improving somewhat at higher  $x_{Bj}$ .

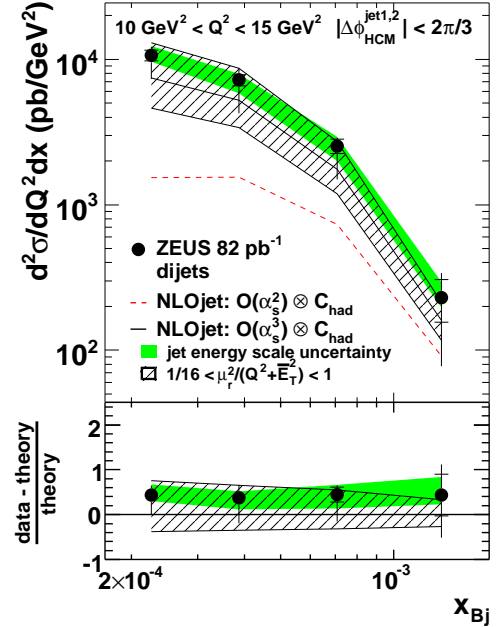


Figure 2: ZEUS dijet cross sections in  $x_{Bj}$  and  $Q^2$  as a function of  $x_{Bj}$  with  $\Delta\phi_{HCM}^{\text{jet1,2}} < 120^\circ$

## 4 Forward Jet Production

To examine the sensitivity of parton evolution to forward jet production, the ZEUS collaboration has studied jet production in an extended pseudorapidity range of  $\eta_{LAB}^{\text{jet}} < 3.5$  by incorporating the Forward Plug Calorimeter (FPC)<sup>7</sup> used during the HERAI running period<sup>8</sup>. Measurements of cross sections as functions of  $Q^2$ ,  $x_{Bj}$ ,  $E_{T,LAB}^{\text{jet}}$ , and  $\eta_{LAB}^{\text{jet}}$  are reasonably well-described by DGLAP-based calculations from DISENT<sup>9</sup>, with large theoretical uncertainties at both low  $x_{Bj}$  and high  $\eta_{LAB}^{\text{jet}}$ . Predictions from LEPTO (DGLAP); ARIADNE<sup>10</sup> (CDM); and CASCADE, with two sets from the J2003 unintegrated gluon PDF used, were also compared to the measurements. Overall, ARIADNE provides the best description of the measured cross sections; LEPTO consistently underestimates the cross sections, and CASCADE fails to consistently reproduce the shapes of the distributions (see Fig. 3).

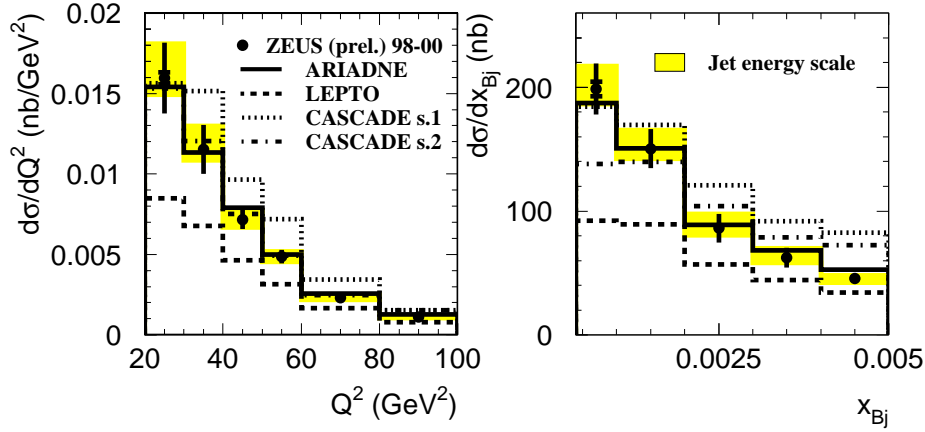


Figure 3: ZEUS forward jets as a function of the kinematic variables  $x_{Bj}$  and  $Q^2$  compared to predictions from ARIADNE, LEPTO, and CASCADE

## 5 Trijet Production and Correlations

Trijet cross sections and correlations were measured by the H1 collaboration as a study of parton evolution at low  $x_{Bj}$ <sup>11</sup>. Cross sections were measured as functions of  $x_{Bj}$ , jet pseudorapidity, scaled jet energies, and correlations in the jet angles  $\theta'$  and  $\psi'$ . The variable  $\theta'$  is defined as the angle between the proton beam and the jet with the highest transverse energy, while  $\psi'$  is defined as the angle between the plane defined by the proton beam and the highest  $E_T$  jet, and the plane defined by the two jets with the highest  $E_T$ . These measurements were made for three separate trijet samples: an inclusive trijet sample, and two trijet samples with one and two forward jets, respectively, with a forward jet having  $\theta_{LAB}^{\text{jet}} < 20^\circ$  and  $x_{jet} = E_{HCM}^{\text{jet}}/E_{pbeam} > 0.035$ . For the inclusive trijet sample, NLOJET calculations provide a reasonable description of the measured cross sections, but slightly underestimate the

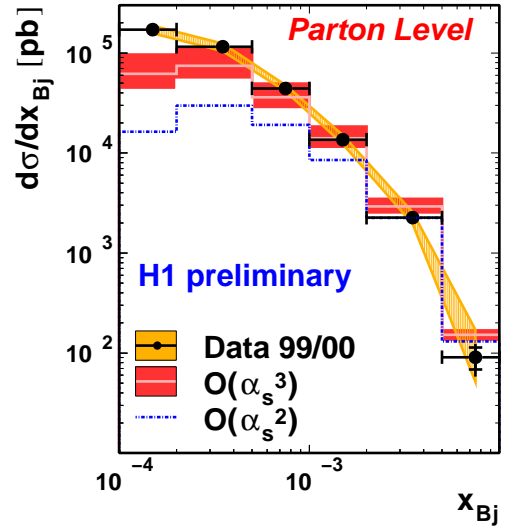


Figure 4: H1 trijet cross sections as a function of  $x_{Bj}$  for events with two forward jets compared to NLOJET calculations at  $\mathcal{O}(\alpha_s^2)$  and  $\mathcal{O}(\alpha_s^3)$ .

measurements in the lowest bin of  $x_{Bj}$ . The agreement between the calculations and the measured cross section in  $x_{Bj}$  is worse for the trijet sample containing two forward jets, with the most noticeable disagreement observed at lowest  $x_{Bj}$  (see Fig. 4). The selection of two forward jets favors events with forward gluon emission unordered in transverse momentum, which the calculations at  $\mathcal{O}(\alpha_s^3)$  do not predict entirely. Also seen in Fig. 4 is that the higher-order terms in the NLOJET calculations are important for forward jet emissions. The other cross sections for this sample are well-described by the calculations.

Predictions from DJANGO (CDM) and RAPGAP LO MC models were also compared to the measured cross sections. The cross sections for the inclusive trijet sample are better described by CDM predictions, but both the CDM and RAPGAP predictions are inconsistent for the jet correlation angles  $\theta'$  and  $\psi'$ ; the RAPGAP predictions fail to describe the  $\theta'$  distributions, and the CDM predictions fail to describe the  $\psi'$  cross sections.

## 6 Summary

Parton dynamics at low  $x_{Bj}$  ( $10^{-4} < x_{Bj} < 10^{-2}$ ) have been investigated at HERA by the ZEUS and H1 collaborations. DGLAP-based NLO calculations describe the measured cross sections and jet correlations reasonably well for the most part when higher-order terms in the calculations are properly taken into account. The calculations fail to describe the trijet cross section in  $x_{Bj}$  when the trijet sample contains two forward jets. Leading-order Monte Carlo models provide an inconsistent description of the measured cross sections. DGLAP-based LO MC models in general do not describe the cross sections; CDM models fail to describe  $\Delta\phi^*$  and  $\psi'$ ; CASCADE predictions are highly sensitive to the unintegrated gluon PDF used, and do not describe the data consistently.

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